Maneuver Analysis and Targeting Strategy for the Stardust Re-Entry Capsule

Cliff Helfrich[*], Ramachand S. Bhat[†], Julie A. Kangas[‡], Roby S. Wilson[§], Mau C. Wong[**], Christopher L. Potts[††], Kenneth E. Williams [‡‡]
Jet Propulsion Laboratory, Pasadena, CA 91109

The Stardust Sample Return Capsule (SRC) returned to Earth on January 15, 2006 after seven years of collecting interstellar and comet particles over three heliocentric revolutions, as shown in Figure 1. The SRC was carried on board the Stardust spacecraft, as shown in Figure 2. Because the spacecraft was built with unbalanced thrusters, turns and attitude control maintenance resulted in undesirable delta-v being imparted to the trajectory. As a result, a carefully planned maneuver strategy was devised to accurately target the Stardust capsule to the Utah Test and Training Range (UTTR). This paper provides an overview of the Stardust spacecraft and mission and describes the maneuver strategy that was employed to achieve the stringent targeting requirements for landing in Utah. In addition, an overview of Stardust maneuver analysis tools and techniques will also be presented.

I. Introduction

The Stardust spacecraft was launched on February 7, 1999 with the primary objective of collecting 500 dust particles during the close encounter with comet Wild-2 and returning them to Earth. The Stardust spacecraft was designed, built, and operated by Lockheed Martin Astronautics (LMA), Denver, CO. The Jet Propulsion Laboratory (JPL) of California Institute of Technology was responsible for project management, mission design, navigation, and mission management. Mission operations were conducted with strong interaction between JPL and LMA. The Deep Space Network (DSN), managed by JPL, provided tracking, telemetry, and telecommunication support. The spacecraft operation control center was located at LMA, Denver, CO.

The spacecraft was expected to perform other tasks, in addition to collecting comet particles, during the Wild-2 flyby namely: a) obtain images of the nucleus of comet Wild-2 during the flyby, b) measure quantity and quality of particles impacted during flyby using the Dust Flux Monitor Instrument (DFMI), and c) Perform spectroscopic analysis of chemical composition of particles observed using the Cometary and Interstellar Dust Analyzer (CIDA). The spacecraft was also expected to collect interstellar samples before and after Wild-2 flyby. Most of these objectives were accomplished by January 2, 2004 after flying through the Wild-2 comet dust tails. The spacecraft returned to Earth with an abundance of comet coma particles based on the number of particle hits seen in the DFMI.

The Stardust trajectory was designed to complete two orbits around the Sun before encountering Wild-2 comet (Fig. 1). Stardust began collecting interstellar dust for four months beginning from August 5, 2002 during its second orbit. Also the trajectory was slightly adjusted to flyby the asteroid Annefrank on November 2, 2002 at a distance of approximately 3000 km. The Stardust spacecraft made its rendezvous with comet Wild-2 with a flyby distance of approximately 236 km on January 2, 2004, shortly after the beginning of the third orbit. The spacecraft completed the third orbit before heading back to the Earth for re-entry on January 15, 2006 [1].

[*] Senior Member of Technical Staff, 4800 Oak Grove Dr., M.S. 301-276, nonmember of AIAA
[†] Senior Member of Technical Staff, 4800 Oak Grove Dr. M.S. 264-820, nonmember of AIAA.
[‡] Senior Member of Technical Staff, 4800 Oak Grove Dr. M.S. 301-150, nonmember of AIAA.
[§] Senior Member of Technical Staff, 4800 Oak Grove Drive M.S. 301-125, nonmember of AIAA.
[**] Senior Member of Technical Staff, 4800 Oak Grove Drive M.S. 301-276, nonmember of AIAA.
[††] Technical Group Supervisor, 4800 Oak Grove Drive M.S. 301-276, nonmember of AIAA.
[‡‡] Senior Member of Technical Staff, 4800 Oak Grove Dr. M.S. 301-150, nonmember of AIAA.

II. Stardust Spacecraft Design

The Stardust spacecraft, as shown in Figure 2, is a three-axis stabilized spacecraft. Stardust has a star tracker with analog sun sensors as backup, but also provides an inertial measurement unit (IMU) with gyros and accelerometers allowing for some closed-loop control of propulsive maneuvers. Thrusters are located on the opposite side of the space vehicle from sample collectors to minimize contamination of samples. These include two strings (prime and backup) of four main thrusters (1 lbf each) used for trajectory correction maneuvers (TCMs) and four reaction control subsystem (RCS) thrusters (0.2 lbf each) supporting attitude control and turns before and after the main burn. Thrusters so positioned do not produce balanced torques, so that all attitude control maneuvers contribute a translational Δv in addition to intended propulsive maneuvers. These small forces must be taken into account for orbit determination purposes and for propulsive maneuver design purposes. Power is provided by solar arrays with a battery in reserve, limiting time at which the spacecraft can point far off Sun.

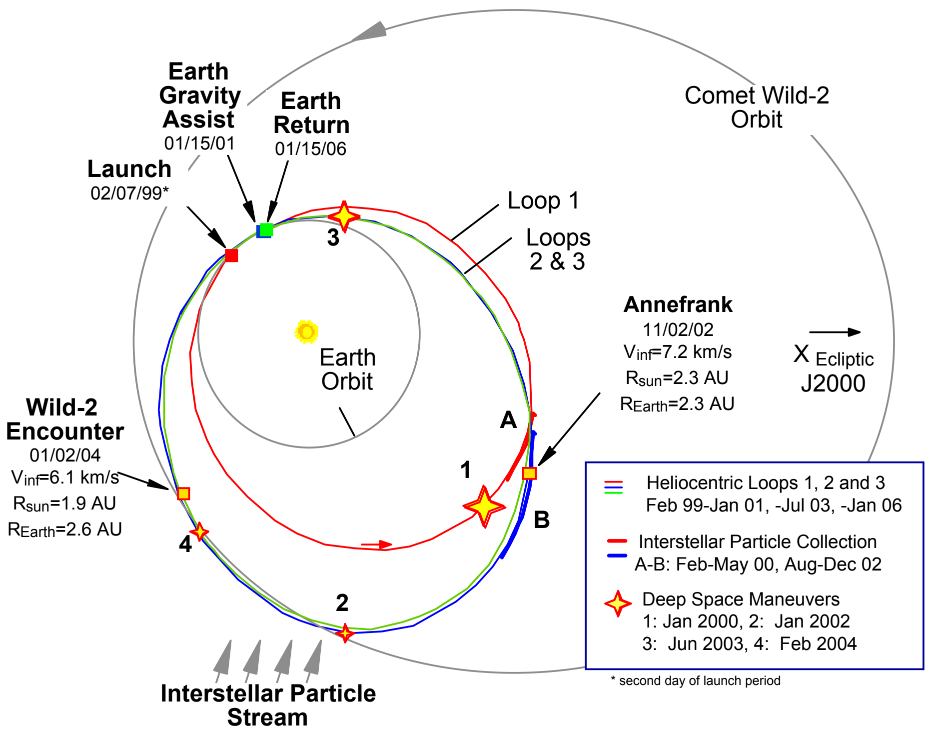

Figure 1. Stardust Heliocentric Trajectory

Most TCMs performed by Stardust have proven difficult to predict accurately. In particular, fixed errors, originally estimated before launch to be only 2 mm/sec, 1-sigma[2], have grown as large as 5 cm/sec, after reconstruction of TCMs. While this level of error is acceptable for much of the mission, including the approach and encounter with comet Wild 2, such error is unacceptable in terms of successful delivery of the SRC at Earth entry. The larger execution error arises from "bang-bang" controlled slews and settling associated with attitude clamping and other components of the TCM sequence itself, effects which are difficult to predict. For slews, the spacecraft changes orientation by accelerating to a maximum turn rate near the initial attitude with corresponding deceleration and settling near the target attitude. This is accomplished exclusively via RCS thrusting. These slews are used to turn to the TCM attitude, then back to Earth pointing for communications purposes. Settling Δv in particular has been difficult to model accurately, perhaps because of sloshing of fuel inside tanks and flexing of various structural components.

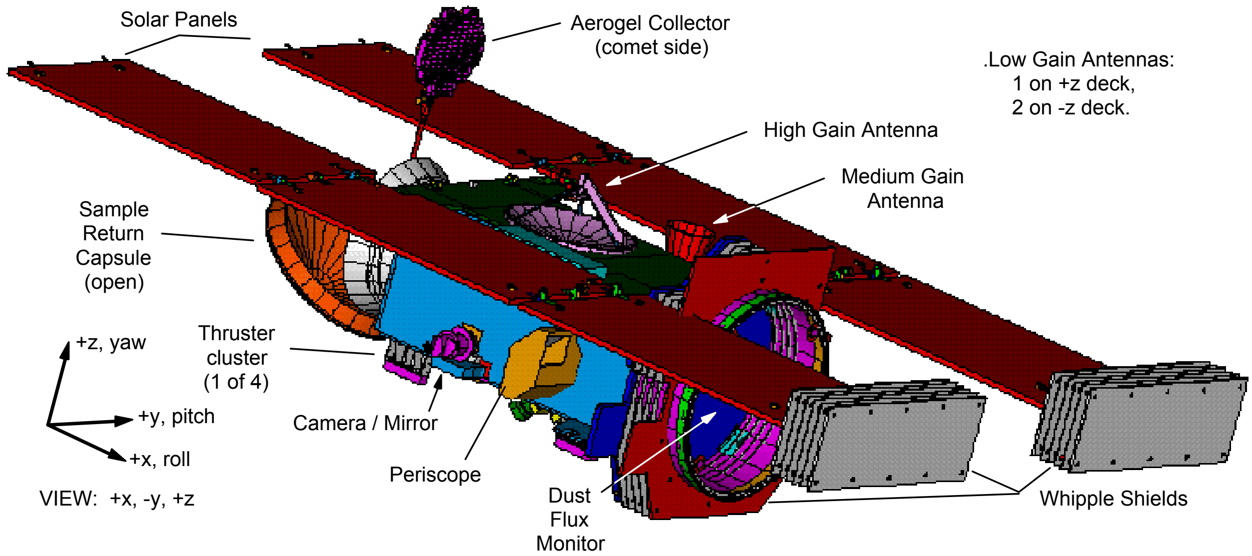

Figure 2. Stardust Spacecraft with Sample Return Capsule Attached

As an alternative to "bang-bang" slews, it is possible to turn the spacecraft by slowly adjusting the deadband box to move towards a target attitude. Such deadband walks involve a maximum turn rate of 1.5 °/min or less and are therefore practical only for attitudes close enough to the Sun such that a healthy power state can be assured over substantial time periods. With deadband walks, fixed errors comparable to the 2 mm/sec, 1-sigma, pre-launch estimates for TCMs are achievable. Stardust closed-loop burns have proven to be fairly accurate (<1% or so, 1σ). However, errors associated with post-burn settling and slews to and from the burn attitude, as well as small forces arising from deadband limit cycling for attitude maintenance, have proven to be much larger than anticipated prior to launch.[1]

III. Maneuver Strategy

Three maneuvers were executed within the last 60 days of the Stardust approach to Earth. The maneuver at 60 days out (TCM-17) was used to clean up the effects of calibration burns performed in the previous weeks, as well as to keep the spacecraft off an Earth impact trajectory. It was desired to avoid an impacting trajectory as long as possible to prevent an undesirable Earth entry in the event of a spacecraft failure. Calibrations were performed in the summer and fall of 2005 to better characterize spacecraft behavior at pre-entry spacecraft attitudes, as well as characterize maneuver execution errors. Late modifications to the calibrations and subsequent spacecraft attitude were needed to mitigate vulnerabilities of the attitude control system (ACS) on Earth approach. TCM-17 was planned with the intent on keeping the spacecraft off an Earth impact trajectory. TCM-17 was 4.17 m/s.

TCM's 17 and 18 were targeted to atmospheric entry conditions, taking into account future propulsive events, such as TCM-19 and the SRC release Δv. This is a target in the atmosphere that results in a precise ground target landing. The targets for these maneuvers are flight path angle (FPA), range, and declination. The values were –8.2 degrees, 6503.139 km, and 41.615 degrees, respectively. The RA and entry epoch were iterated in an outer search loop to meet the longitude target in light of other targeting constraints. The right ascension target was 140.004 deg and the initial guess for the entry epoch was15-JAN-2006 09:58:10.6 ET. TCM's 17 and 18 were also targeted through all known Δv events that were known at the time. This includes small force Δv predictions, future TCM's, and the release Δv, which was about 0.34 m/s as felt by the return capsule. TCM-17 was targeted through TCM-18, which was biased at 1.406 m/s in a sunward direction, and TCM-19, which was biased at 1 m/s along the +z at the release attitude.

The next maneuver (TCM-18) was executed 10 days from Earth entry. This maneuver was biased to assure that large turns (slews) would not be required to get to the burn attitude. Slew maneuvers were very unpredictable on Stardust and imparted large errors to the trajectory. TCM-18 was 2.39 m/s.

During the TCM-18 design cycle, a matrix, Figure 3, was constructed to examine the potential impact of TCM-18 on the final targeting at Earth. The vertical axis describes the small force model on which the TCM-18 design would be based. A nominal small force model, along with 15% high and low cases were analyzed. Then, for study purposes, after TCM-18 was to be executed, the small force model would be varied again to examine the effects on TCM-19 in case of faulty small force modeling. The small force range for TCM-19 would vary from 30% low to 15% high. The matrix boxes first list values for TCM-18, which are constant across each row, based on a given small force model used in the TCM-18 design. Next, TCM-19 values are listed. Then ground crosstrack errors are shown which result after executing a fixed-direction TCM-19. The entry interface time (EI) is also shown for each case.

It was desired to keep TCM-19 in the calibrated neighborhood of 1.0 m/s or greater. As a result, it was preferred to stay in the lower left side of the matrix. TCM-18 was therefore designed with greater than expected small forces to maintain a high probability of keeping TCM-19 greater than 1 m/s. The residual crosstrack error was considered, but, since it was small in comparison to the expected dispersions due to atmospheric uncertainties alone and with perfect navigation (45 km x 19 km), this error was deemed secondary to maintaining TCM-19 in the calibrated range.

TCM-19 based on Small Forces Predicted Acceleration of…

TCM-18 based on Small Forces Predicted Accel…	-30%	-15%	Nominal	+15%
-15%	<-- **18:** 2.832 m/s **19:** 1.372 m/s **Xtrk:** 1.77 km N **EI:** 09:57:46.5 ET	@ 16.3¡ off 1.0 m/s 0 09:57:46.0 ET	Sun ---------- 0.628 m/s 1.79 km S 09:57:45.4 ET	--------> 0.256 m/s 3.57 km S 09:57:44.9 ET
Nominal	<-- **18:** 2.692 m/s **19:** 1.745 m/s **Xtrk:** 3.56 km N **EI:** 09:57:47.1 ET	@ 16.9¡ off 1.372 m/s 1.78 km N 09:57:46.5 ET	Sun ---------- 1.0 m/s 0 09:57:46.0 ET	--------> 0.628 m/s 1.78 km S 09:57:45.4 ET
+15%	<-- **18:** 2.552 m/s **19:** 2.117 m/s **Xtrk:** 5.34 km N **EI:** 09:57:47.7 ET	@ 17.6¡ off 1.745 m/s 3.56 km N 09:57:47.1 ET	Sun ---------- 1.372 m/s 1.78 km N 09:57:46.6 ET	--------> 1.0 m/s 0 09:57:46.0 ET

Figure 3. TCM-18 Parametric Design Matrix

The time of the final maneuver (TCM-19) changed as a result of studies performed throughout the year prior to Earth return. The original plan was to perform TCM-19 at 48 hours prior to entry. Then, to reduce the size of the ground footprint, this maneuver was moved to 36 hours prior to entry. At this time, it was proposed to burn in a fixed, predetermined direction. There were several advantages to a fixed burn direction strategy. First, this expedited maneuver planning and testing by the spacecraft team. The shortened timeline required by the spacecraft team allowed for use of the latest possible orbit determination data in the planning of TCM-19. This additional orbit determination data resulted in a decrease in the flight path angle error. Another benefit of burning in a fixed direction was that no turns were required to achieve burn attitude. As was stated earlier, Stardust's unbalanced thrusters imparted undesirable and unpredictable Δv to the trajectory when executing turns. The fixed burn direction strategy limited the effect of uncertainties in turn Δv prior to SRC release. However, as a result of burning in a fixed direction, this maneuver only corrected downtrack errors on the ground.

The fixed burn direction was determined by the SRC release attitude. Stardust began in the corresponding Sun-relative attitude between TCM's 18 and 19. TCM-19 was executed at this attitude at 29 hours prior to Earth entry, and the spacecraft came out of this burn in an inertially fixed attitude. Originally, the roll attitude put the Δv direction in the Sun-SRC release plane. It was discovered that in this attitude, the Moon could potentially blind the star trackers near Earth. Thus the final roll orientation was set at 20° different from the original plan. This 20° rolled attitude was accounted for prior to the final limit cycle calibrations, so the navigation team was able to roughly characterize the small force performance at this attitude prior to TCM-18. More information on the calibrations can be found in Reference 3.

Figures 4 and 5 show the different ground ellipses resulting from these two possible strategies for TCM-19. Figure 4 shows the ground dispersion ellipse resulting from a full design TCM-19 strategy at one day before entry. The crosstrack dispersions are smaller than the ellipse associated with a fixed direction burn shown in Figure 5 (19 km vs. 29 km). Although the time of the two burns is slightly different, 24 hours out in Figure 4 and 29 hours out in Figure 5, this should not make a significant difference and the relative difference in the shape of the ground ellipses between these two strategies is still valid. As a result of the residual cross-track errors resulting from a fixed-burn strategy, a range of possible small force conditions were examined to ensure that cross-track errors not corrected at TCM-19 would be acceptable. TCM-19 was also biased at 1 m/s to assure a burn magnitude that was not too small.

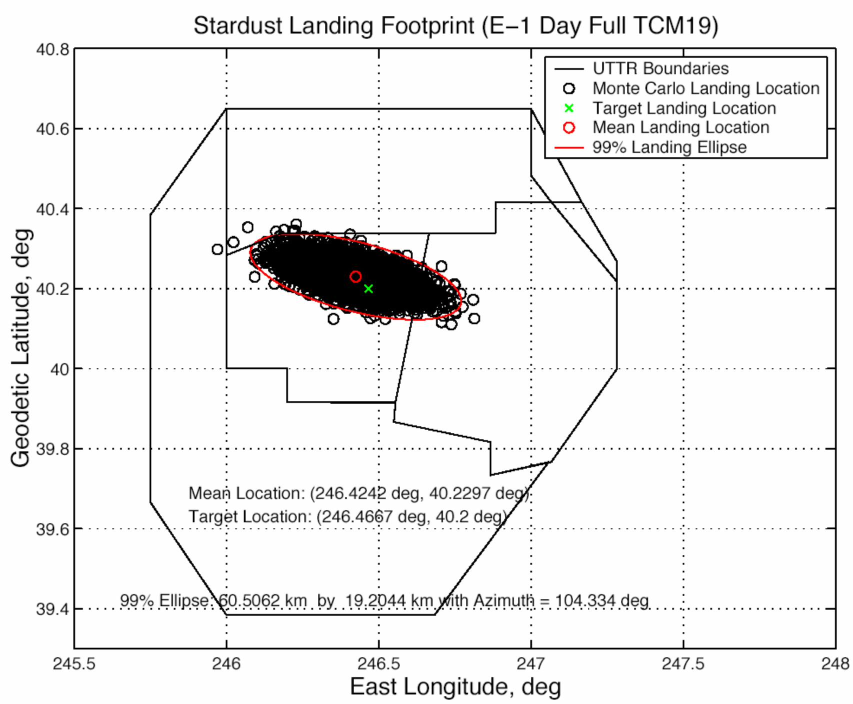

Figure 4. Full design TCM-19 at E-24 hours

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Figure 5. Fixed direction burn at E-29 hours

In the summer and early fall of 2005, calibrations were performed to test spacecraft maneuver performance in the range of approximately 0.5 to 1.0 m/s. One outcome of these calibrations was a refinement of the Stardust execution error model. This refined execution error model is summarized in Figure 6. This refinement of the error model led to moving TCM-19 to 29 hours prior to Earth entry. This time was chosen for operational robustness. A TCM-19 at 29 hours out allowed for overlapping DSN station coverage for both maneuver uplink and execution. Another advantage was in workforce staffing. Since the SRC release occurred 25 hours after TCM-19, it was easier to have the same navigation personnel monitor both events. Another result of the calibration campaign was that biases were applied to all subsequent maneuvers. Consistent overburns, along with extra Δv from settling events, led to the implementation of a bias which was subtracted from the designed, ideal Δv to determine the spacecraft's commanded Δv. More details on the calibrations can be found in Reference 3.

Propulsive Maneuver (Burn with Settling Effects)

Case	*Max Magnitude Error (3 σ)*	*Max Direction Error (3 σ)*	*Notes*
Fixed Attitude (TCM-19 and Sunward TCM-19x)	1.7% and 9 mm/sec	1.5% and 5 mm/sec	Based on ACS simulation results; calibrated results over range of 0.5-1.0 m/s (EMDs 5-16) fall well within this performance envelope.
Full Design (All Other TCMs)	1.7% and 7.5 mm/sec	1.5% and 5 mm/sec	Smaller fixed magnitude error due to removal of pointing correction at end of burn (would occur at end of final turn instead).

Attitude Maneuver (Turns - 2-Way)

Type	*Maximum Error per Axis (3 σ)*	*Notes*
Deadband Walks	4 mm/sec pitch, 1.5 mm/sec roll	Based on 2003 Deadband Walk Calibrations (1.5 deg/min; calibrated within 40 deg); calibrations at 60 deg in progress.
Slews to/from Antisunward Attitude	5 cm/sec	Based on more recent flight performance (predominantly in roll direction).
All Other Slews	15 cm/sec	Conservative enough to exceed worst result ever observed in flight.

Figure 6. Execution Error Model

In the event of an anomaly such as a safe-mode event, a contingency maneuver was to be performed at 12 hours out from Earth entry, or 17 hours after TCM-19. This maneuver was to be executed in either fixed-direction mode, TCM-19a, or as a "full-design" burn, TCM-19b, which could burn in any direction. The determining factor between these two modes was a "build map" which was to be used in the event this maneuver was needed. The pre-manuever trajectory was to be run down to the ground and this ground location decided which burn mode was needed, as shown in Figure 7 (build map). If the capsule was shown to be landing within 15 km of the nominal target, no contingency maneuver would be executed. If the capsule was on course to land in the general downtrack (southeast) direction, a fixed-direction burn would be implemented (TCM-19a). This region is described as "A" in the build map. This burn direction was to be the same as the nominal TCM-19 direction, and would result in a residual cross-track error. Most other possible landing locations would require a burn in a different direction (TCM-19b). These regions are described as "B" on the build map. If TCM-19b turned out to be less than a value which was calibrated (around 0.35 m/s), the target was to be changed to introduce a cross-track component to increase the Δv into the calibrated range. Alternate targets of 5, 10, and 15 km to the southwest of the nominal were to be used in this case. The southwest targeting was desirable to keep the capsule away from the yellow divot region shown in Figure 7. A landing in this area would be the result of overflying populated regions to the east of UTTR.

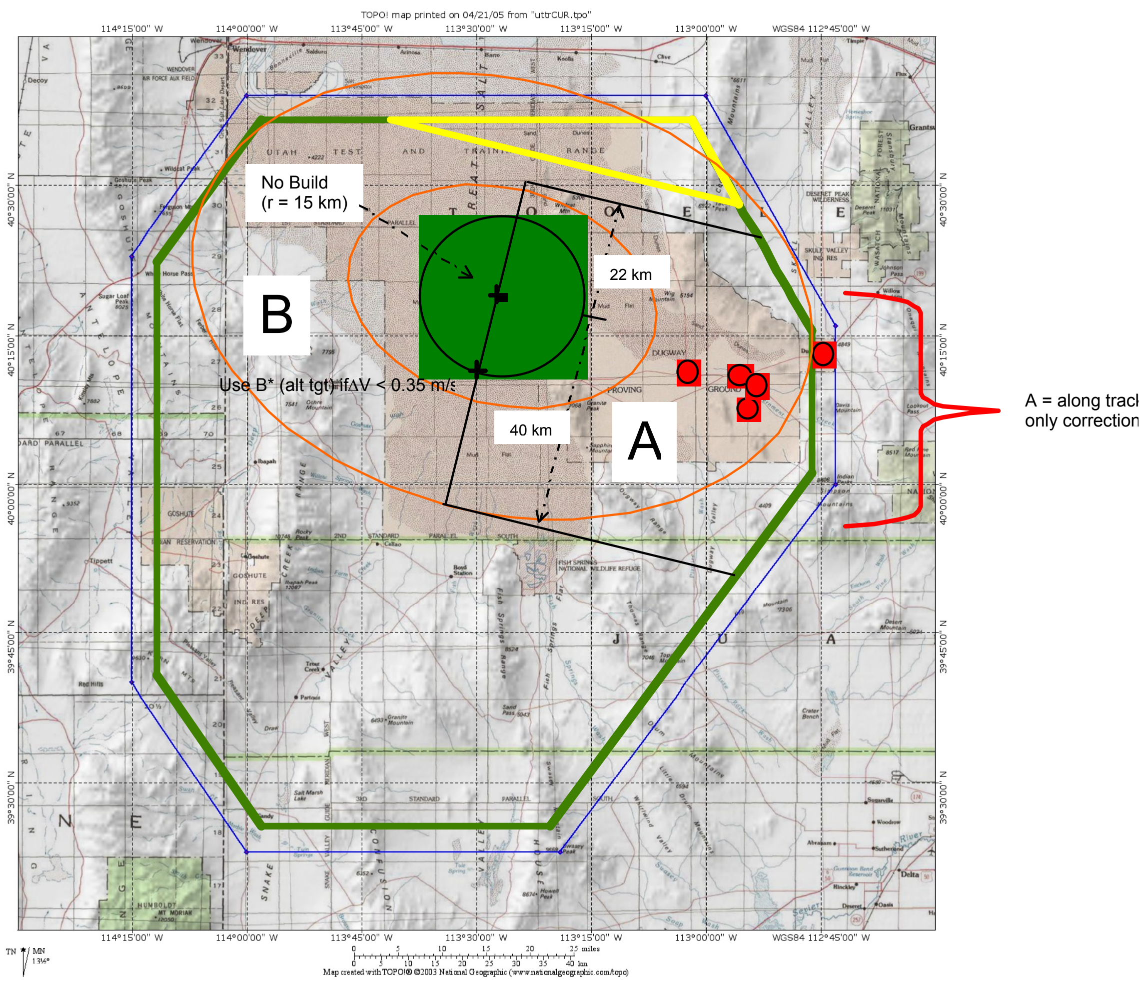

Figure 7. TCM-19a/b Build Map

IV. Implementation

Two maneuver types were considered for the final TCMs; a maneuver at a fixed attitude that would correct along track errors only or a maneuver at any attitude that would target directly to the nominal landing site. Bourne shell scripts were written to facilitate the analysis of each maneuver type.

The initial iteration of the fixed direction maneuver script (tcmFixedDir.sh) uses a small ΔV in the direction of the fixed attitude. The entry vehicle state is propagated with PDRIVE, a high precision trajectory propagator, to the atmospheric entry interface point. The spacecraft separation ΔV is included in the propagation. The time and state of the entry vehicle at entry is passed to AEPL, an atmospheric propagator and search program. In this script, AEPL is used in propagation mode only and determines the landing location based on the entry state and time. This landing location is then compared to the nominal landing site and a refined value of ΔV is calculated to bring the landing location closer to the nominal location. This refined ΔV value is calculated based on previously generated partials which relate ΔV at the maneuver epoch to ground displacement. The script iterates until the distance to the desired landing site is a minimum, achieving convergence, and the offset in landing location from the nominal is in the cross track direction only. This method results in a small offset in flight path angle from the nominal value.

The initial iteration of the free attitude maneuver script (fullDesign.sh) begins with an estimate of the time of entry and the B-plane angle at entry. A high fidelity trajectory search program, SEPV, is used to target the entry vehicle to these entry conditions and the desired entry flight path angle of -8.2º. As in the previous script, the spacecraft separation ΔV is included in the search. The entry vehicle time and state at entry is then passed to AEPL which in this case is used in the targeting mode. AEPL calculates updated entry conditions (time and B-plane angle) needed to reach the desired landing location. These updated entry conditions are passed back to SEPV and the process is repeated until the entry time is changing by less than 0.15 seconds. This method results in both the landing location and the entry flight path angle conditions being met.

In addition, because statistical entry state software did not accurately model a fixed direction Δv strategy, a new method to model trajectory dispersions was used to account for this unique targeting strategy. This technique, developed to more accurately model the control strategy in a Monte Carlo fashion, was called META (Maneuver and Entry Targeting Analysis).

The algorithm for META is described in Figure 8. Basically, META allows all errors incurred at the previous maneuver to be fully accounted for in the design of the current maneuver. Operationally, the outcome of the previous maneuver is always reconstructed prior to the design of the current TCM, yielding a spacecraft state which is well characterized and bounded by relatively small knowledge covariances. However, for advanced Monte-Carlo studies, many outcomes are possible for spacecraft states after the previous TCM. TCM-19, constrained to a fixed attitude, was targeted only to entry flight path angle or the corresponding position along the prevailing ground track. Thus, TCM-19 was not designed to correct cross-track position. Execution errors at TCM-18, giving rise to cross-track errors at Earth entry or at the ground target, but not intentionally corrected by TCM-19, needed to be properly mapped forward and not discounted, yielding more realistic, conservative entry and ground target dispersions.

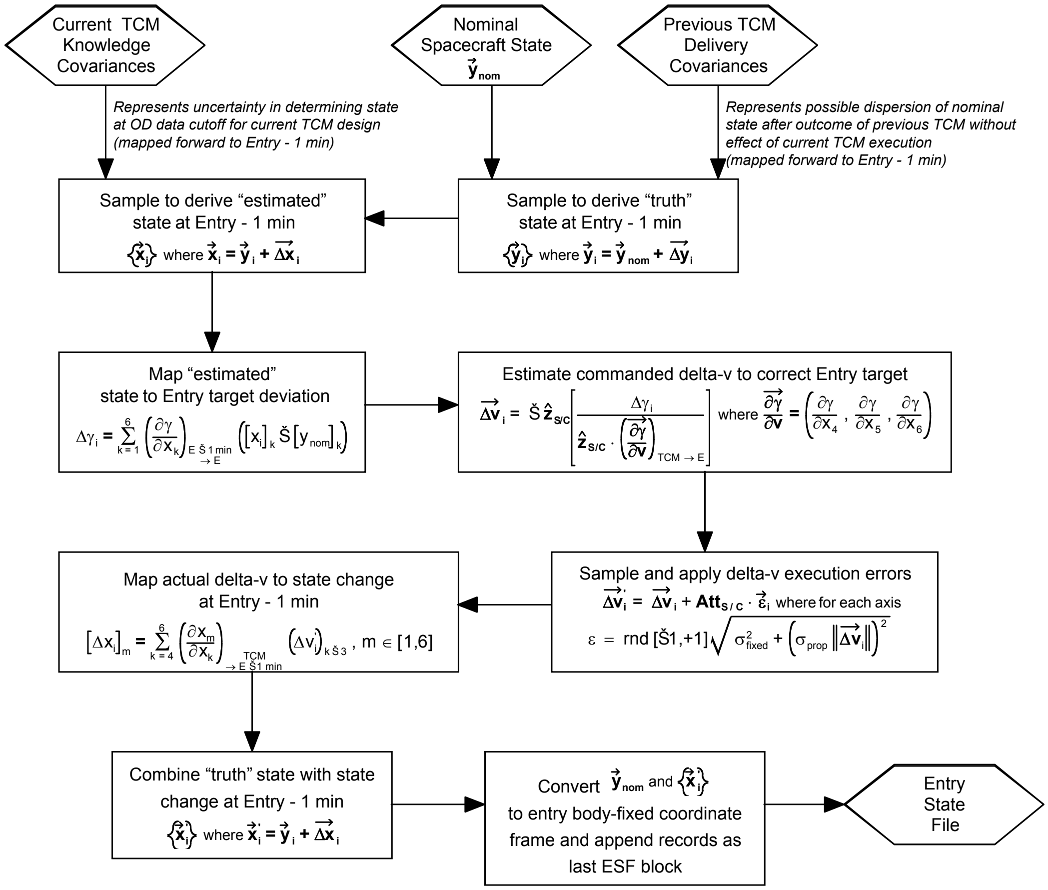

Figure 8. META Algorithm

V. Conclusion

The design of TCM-19 went as planned. The maneuver design scripts, described earlier and which tied together several different pieces of software into one executable, allowed for a very tight maneuver design timeline. The maneuver design team was only allowed 30 minutes to design the final maneuver (TCM-19) after receiving a solution from the orbit determination team. The development of these scripts made this quick maneuver design possible, although this was still a stressful 30 minutes.

TCM-19 was executed at 1.3 m/s as shown in Table 1. The SRC release occurred 4 hours prior to Earth entry. The delivery was well within the original 0.08° (3σ) flight path angle uncertainty. The SRC landed very close to the ground target, shortly after 3:00 AM local time on January 15, 2006. As shown in Figure 9, the actual landing location (indicated as the “GPS Location” in red) is about 9.7 km from the targeted landing point. Most of this offset was due to windy conditions at UTTR. This offset was well within the expected dispersions due to atmospheric uncertainties alone, which was 45 km x 19 km.

The Stardust experience underscores the importance of balanced thrusters on sample return missions. The lack of balanced thrusters on Stardust greatly complicated the return navigation. Continuous small-force monitoring and small-force trade studies absorbed a large amount of time and resources.

In conclusion, it is strongly recommended by the authors that all future sample return missions undertake extensive trade studies during Phase A/B to understand the consequences of spacecraft designs, such as unbalanced thrusters, before making the hardware selection. A more systematic, end-to-end assessment of mission requirements and capabilities is called for to avoid merely passing on such problems to Phase E with greatly increased risk and deferred costs.[2]

Event	Epoch (UTC)	Final Design Δv (m/s)
TCM-17	16-Nov-2005 21:00	4.17
TCM-18	05-Jan-2006 18:00	2.39
TCM-19	14-Jan-2006 04:54	1.30
Entry	15-Jan-2006 09:57	---

Table 1. Earth Return TCM Summary

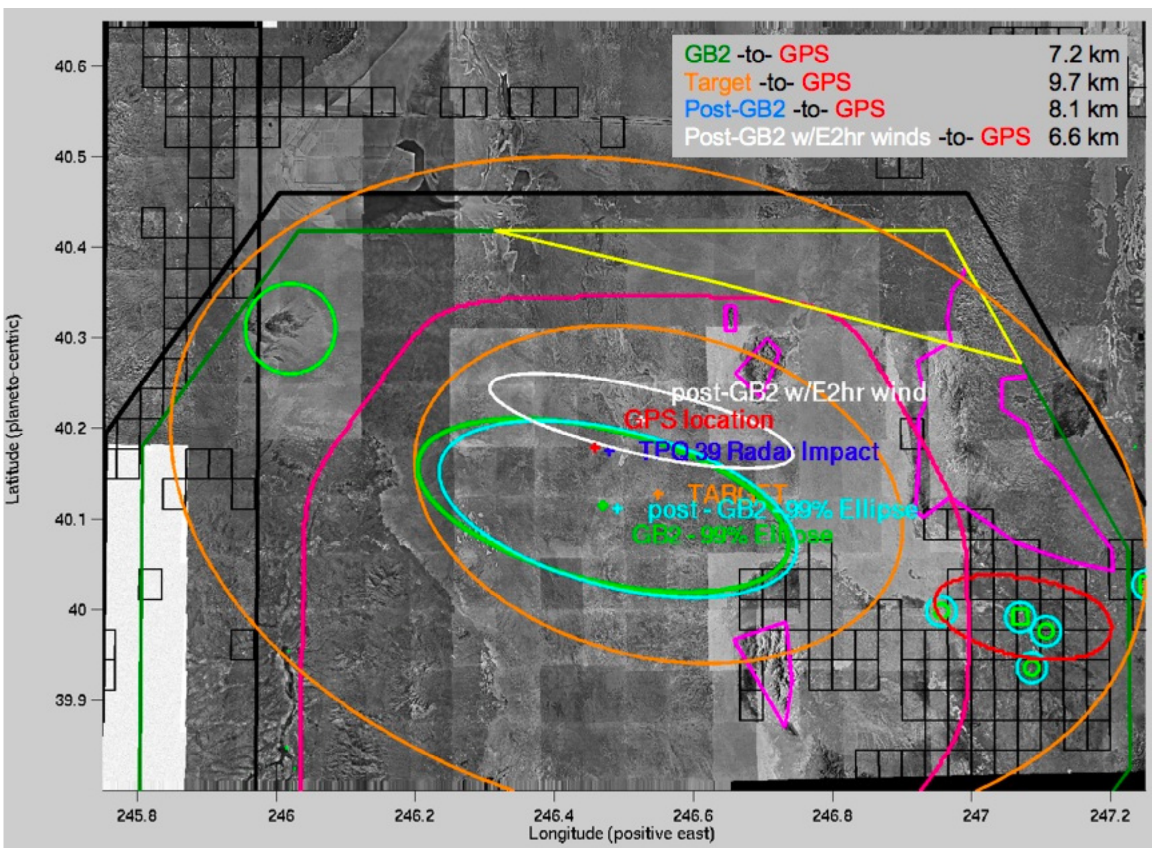

Figure 9. Stardust SRC Final Delivery to UTTR

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Acknowledgments

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